REPORT 992

THEORETICAL COMPARISON OF SEVERAL METHODS OF THRUST AUGMENTATION FOR TURBOJET ENGINES

By Eldon W. Hall and E. Clinton Wilcox

SUMMARY

A theoretical investigation of tail-pipe burning, water injection at the compressor inlet, combination tail-pipe burning plus water injection, bleedoff, and rocket-assist methods of thrust augmentation for turbojet engines was made for an engine representative of those in current use. The effect of augmented liquid ratio on augmented thrust ratio and the effects of altitude and flight Mach number on the performance of the various methods were determined. The additional take-off weight involved by the use of the different thrust augmentation methods, as well as the effect of the various thrust augmentation methods on the range of a representative aircraft, was also investigated.

Results indicated that the combination tail-pipe burning plus water injection method was best for large amounts of thrust augmentation and that the tail-pipe burning method was best for smaller amounts inasmuch as both methods had lower augmented liquid ratios for given augmented thrust ratios than any of the other methods considered.

For take-off conditions, the maximum augmented thrust ratio for the combination tail-pipe burning plus water injection method was 1.9 at an augmented liquid ratio of 7. For the tail-pipe burning method, the maximum augmented thrust ratio was 1.5 at an augmented liquid ratio of 4. An increase in flight Mach number greatly increased the augmented thrust ratio produced by all methods investigated. Increasing the altitude decreased the augmented thrust ratio somewhat for those methods employing water injection and had a very small effect on the augmented thrust ratio for the tail-pipe burning method. Increasing the engine compressor pressure ratio increased the maximum attainable augmented liquid ratio and thereby increased the maximum possible augmented thrust ratio.

A comparison on the basis of additional take-off weight indicated that the best method of augmentation depended on the required amount of thrust augmentation and that each method was best for a certain range of augmented thrust ratios.

For a representative aircraft operating at a flight Mach number of 1.50 and an altitude of 35,332 feet, the tail-pipe burning method allowed a slight increase in maximum range and a considerable increase in disposable load. The other methods allowed considerable increase in disposable load at the expense of reduced range.

INTRODUCTION

The widespread use of the turbojet engine has stimulated interest in methods for increasing engine thrust for continued operation as well as for short periods of time. This increased power results in increased effectiveness of the turbojet engine due to attendant improvement in airplane performance.

An analysis of tail-pipe burning, water injection, and bleedoff methods of thrust augmentation is presented in reference 1, which includes a description of the cycles of operation of these augmentation methods and provides an insight into their performance characteristics. In reference 1, the effect of tail-pipe burner design parameters on both normal and augmented engine performance is presented and the effect of water injection both in the compressor inlet and in the engine combustion chamber is discussed. For the bleedoff method, performance is presented for engines having compressor characteristics typical of both axial-flow- and centrifugal-flow-type compressors, and the use of both fixed- and variable-area exhaust nozzles is considered.

In order to obtain a more complete comparison of the various methods of thrust augmentation, it is necessary to consider the effect of thrust augmentation on airplane performance. The load-range characteristics of an aircraft powered by augmented turbojet engines and the additional weight involved by the use of the various methods are considered in this report. In addition to the tail-pipe burning, the water injection, and the bleedoff methods (discussed in reference 1), the combination tail-pipe burning plus water injection and the rocket-assist methods are included in the present investigation. In order to provide a further insight into the operational characteristics of the augmentation methods, engine performance is presented for an extensive range of flight Mach numbers and altitudes. These comparisons were made using engine design parameters and component efficiencies, the choice of which was guided by the results presented in reference 1. The investigation reported herein was conducted at the NACA Lewis laboratory in 1948.

METHODS OF THRUST AUGMENTATION

The principles of engine operation using tail-pipe burning, water injection, or bleedoff methods of thrust augmentation are described in reference 1. The basic principles of these

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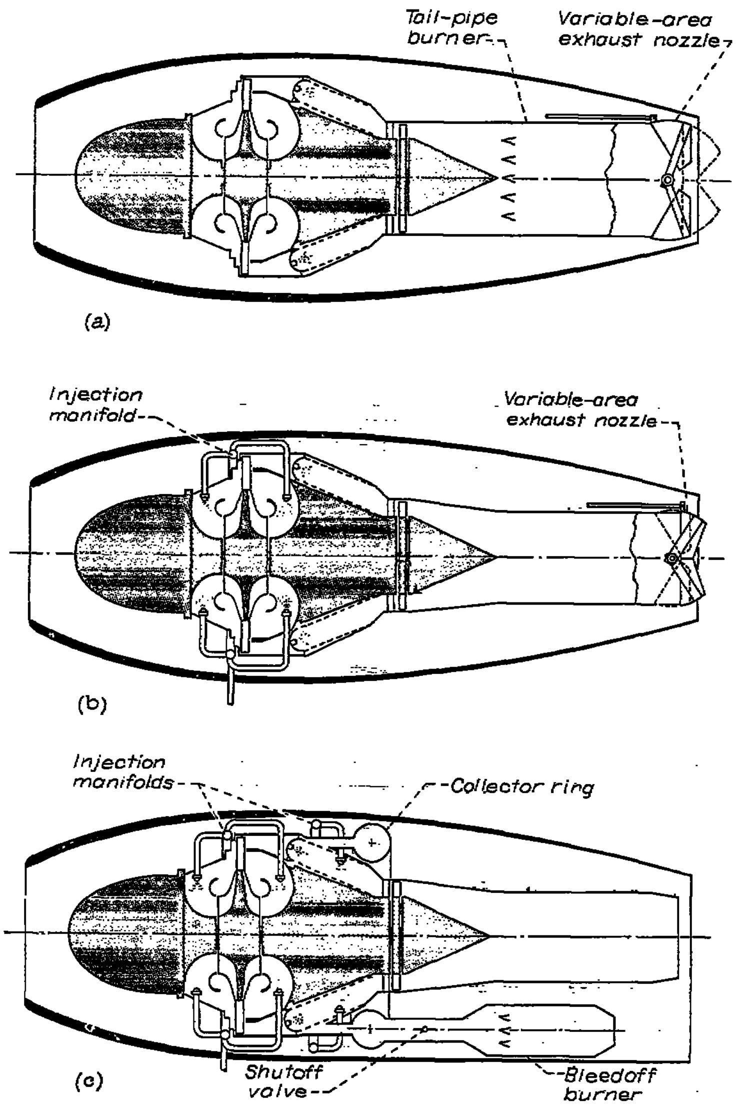
and the other augmentation methods considered in the present report are briefly reviewed.

Tail-pipe burning.—A schematic diagram of a turbojet engine modified for thrust augmentation by tail-pipe burning is shown in figure 1(a). With the tail-pipe burning method of thrust augmentation, additional fuel is burned in the engine tail pipe thus increasing the temperature of the gases entering the exhaust nozzle, and hence increasing the exhaust-jet velocity. The increased jet velocity and, to a lesser extent, the increased fuel mass contribute to increasing the thrust produced by the engine. Because the temperature of the gases in the tail pipe is not subject to the limitations imposed by the turbine materials, burning to much higher temperatures in the tail-pipe burner than in the engine combustion chamber is possible.

Water injection at compressor inlet.—A turbojet engine equipped for thrust augmentation by water injection at the compressor inlet is illustrated in figure 1(b). By the injection of water ahead of the compressor inlet, evaporative



(a) Modified for tail-pipe burning.
(b) Modified for water injection at compressor inlet.
(c) Modified for bleedoff.

FIGURE 1.—Turbojet engine modified for thrust augmentation by various methods.

cooling to the saturation temperature can be obtained prior to mechanical compression. When water in excess of that required to saturate the compressor-inlet air is injected, further cooling is obtained by evaporation during the mechanical compression process. Because the temperature of the fluid throughout the compression process is reduced below that for the dry process, a higher pressure ratio is obtained for a given compressor rotor speed or compressor work input per pound of air-water mixture. This higher pressure ratio is reflected throughout the engine and results in increased engine-air flow and jet velocity; both factors tend to increase the thrust.

In order to prevent freezing during high-altitude operation, a nonfreezing mixture must be used rather than water alone. Alcohol is a desirable substance for this purpose because of its nonfreezing properties and because it replaces some of the fuel that is required in the engine combustion chamber. The present analysis was made for water alone injected in the compressor inlet. Inasmuch as experimental data indicate that the thrust augmentation obtained from water-alcohol injection does not appreciably differ from that obtained using water alone, the results are very nearly correct for water-alcohol mixtures. The use of water-alcohol mixtures may, however, result in a somewhat decreased liquid consumption due to replacement of some fuel with alcohol.

Combination tail-pipe burning plus water injection.—The method using tail-pipe burning plus water injection is simply a combination of the two aforementioned augmentation schemes.

Bleedoff.—The bleedoff method of thrust augmentation entails the modifications to the normal turbojet engine illustrated in figure 1(c). Secondary combustion or excess air, removed either at the compressor outlet or at the engine combustion chamber is ducted to an auxiliary or bleedoff burner where fuel is burned at fuel-air ratios approaching stoichiometric; the gases are then discharged through an auxiliary nozzle. Water is injected in the engine combustion chamber to replace the air that is bled off, and additional fuel is injected to maintain normal turbine-inlet temperatures. As an additional part of the bleedoff method, water is also injected at the compressor inlet to obtain additional augmentation as previously described.

The thrust augmentation of the bleedoff system is provided chiefly by the thrust of the auxiliary jet. Inasmuch as the air that is bled off is replaced with water, the thrust of the primary engine remains approximately constant (depending somewhat upon the compressor characteristics), but at a value higher than that for the normal engine due to the injection of water at the compressor inlet.

Rocket assist.—Rocket assist cannot be considered a thrust augmentation method in the same sense as the other methods considered herein because the turbojet engine remains unchanged and another power plant is simply added to the aircraft. This method is, however, presented for comparison because of the widespread use of rocket assist for take-off and its competitive nature with the augmentation methods considered.

ANALYSIS

In order to evaluate the various thrust augmentation methods, a comparison was made on the basis of (a) the amount of thrust augmentation produced by each method for a range of total liquid consumptions and over a range of flight conditions, (b) the amount of additional take-off weight involved by the use of the various methods, and (c) the influence of each augmentation method on the load-range characteristics of a supersonic aircraft powered by turbojet engines.

CALCULATION OF THRUST AUGMENTATION

The normal and the augmented performances of the engine were determined from step-by-step calculations of the state changes undergone by the working fluid in passing through the engine components in much the same manner as outlined in reference 1. In reference 1, the effects of the principal design and operating variables of the various augmentation methods on over-all engine performance are presented. In the present report, representative values were chosen for the design variables and were maintained constant for the range of flight Mach numbers and altitudes considered. The ambient temperatures and pressures at the various altitudes considered varied in accordance with the NACA standard atmosphere.

For convenience, the assumed values of efficiencies and engine design parameters are presented so that the assumptions that are identical for both normal and augmented engines appear in the section "Normal engine", whereas any additional or altered values that are involved by the use of a particular augmentation method are listed separately.

Normal engine.—For all configurations, the inlet diffuser was assumed to have an adiabatic efficiency of 0.91 at all subsonic flight speeds. For supersonic speeds, the ratio of actual to ideal total pressure for the inlet diffuser was assumed to vary with flight Mach number in the following manner:

Flight Mach number	Total-pressure recovery ratio
1.50	0.93
2.00	.88
2.50	.78

The compressor was assumed to have an adiabatic efficiency of 0.80 and a work input of 75.5 Btu per pound. The resulting compressor pressure ratio at sea-level altitude, zero flight Mach number was 4.0.

In order to illustrate the effect of increased normal compressor pressure ratio, calculations were made for one particular flight condition for an engine having a compressor adiabatic efficiency of 0.80 and a work input of 151 Btu per pound. For this high-pressure-ratio engine, the compressor pressure ratio for sea-level zero flight Mach number conditions was 10.8. For all cases, the work input to the compressor was assumed constant, and hence the compressor pressure ratio varied with compressor-inlet temperature (decreased with increased flight Mach number and increased with increased altitude). A 3-percent loss in total pressure was assumed to occur between the compressor outlet and the turbine inlet. The turbine-inlet temperature was maintained constant at 2000° R and the combustion efficiency was assumed to be 0.95. The turbine adiabatic efficiency was 0.85 and the velocity coefficient of the exhaust nozzle was assumed to be 0.975. The assumption of constant turbine-inlet temperature may require that the engine be equipped with a variable-area exhaust nozzle. Calculations were made for a range of flight Mach numbers from 0 to 2.50 and for a range of altitudes from 0 to 50,000 feet.

Tail-pipe burning.—For the present analysis of the tail-pipe burning method of thrust augmentation, the results of reference 1 were considered. The following values of tail-pipe burner design parameters, which give satisfactory performance and are believed to be readily attainable in actual practice, were chosen: The turbine-outlet velocity was assumed to be 750 feet per second and it was further assumed that the gases were diffused to a velocity of 400 feet per second at the tail-pipe burner inlet. The adiabatic efficiency of this diffusion process was assumed to be 0.80. The drag coefficient of the tail-pipe burner (ratio of total-pressure loss to burner-inlet dynamic pressure) was assumed to be 1.0. The combustion efficiency for the tail-pipe burner was taken as 0.95, and calculations were made for a range of over-all engine fuel-air ratios up to stoichiometric.

Water injection at compressor inlet.—Experimental results indicate that the injection of water at the inlet of a compressor decreases the compressor efficiency; the exact magnitude of this decrease, however, has not been established for a wide range of conditions. In the present report, the compressor efficiency was decreased ½ percent for each percent of water injected in excess of that amount required to saturate the compressor-inlet air in order to provide performance representative of current experimental achievement and hence provide a realistic comparison of the water-injection method with the other methods considered. For all methods in which water injection was employed, the fuel flow to the engine was sufficiently increased to maintain the normal turbine-inlet temperature. The methods used in calculating compressor performance with water injection are described in references 2 and 3. Calculations were made for a range of water injection rates up to that amount required for saturation of the compressor-outlet air.

Combination tail-pipe burning plus water injection.—The assumptions involved in the calculation of the combination tail-pipe burning plus water injection method are simply those previously given for the tail-pipe burning and the water injection methods. Calculations were made for an over-all stoichiometric fuel-air ratio and for various amounts of water injected at the compressor inlet up to that amount required for saturation of the compressor-outlet air. The effect of the difference in specific heat of steam and air was included in calculating combustion temperatures.

Bleedoff.—In reference 1, the bleedoff method was analyzed for engines having compressor characteristics typical of both current axial-flow- and centrifugal-flow-type compressors and for several engine exhaust-nozzle areas. The thrust augmentation was found to be nearly independent of compressor type and exhaust-nozzle area and was dependent chiefly on the additional liquid consumption. For simplicity in the present analysis, the engine exhaust-nozzle area was therefore assumed to maintain the air flow through the compressor at the same value for bleedoff operation as without bleedoff but with water injection at the compressor inlet. This assumption, as shown in reference 1, gave thrust increases nearly equal to those obtained with the optimum exhaust-nozzle area for the axial-flow-type engine and only slightly below the optimum for the centrifugal-flow-type engine. For all cases, sufficient water was injected at the compressor inlet to saturate the compressor-outlet air. The compressor efficiency was adjusted, as previously described, for water injection at the compressor inlet. A 3-percent loss in total pressure was assumed to occur between the compressor outlet and the bleedoff-burner inlet. The bleedoff burner was assumed to have a combustion efficiency of 0.95. Calculations were made for a stoichiometric fuel-air ratio in the bleedoff burner and for a range of bleedoff flows and attendant water injection rates in the engine combustion chamber up to that amount requiring stoichiometric fuel-air ratio in the engine combustion chamber.

Rocket assist.—The rocket-assist method consisted simply in adding sufficient rocket units to obtain the desired thrust. The rockets were assumed to have a specific impulse of 190 pounds per pound per second independent of altitude and flight speed.

TAKE-OFF WEIGHT CONSIDERATIONS

The methods of augmentation were compared on the basis of the ratio of the take-off weight of an augmented engine plus liquids to the take-off weight of a normal engine plus fuel for various amounts of thrust augmentation and for the time required for the take-off operation. No attempt was made to quantitatively evaluate performance changes due to required changes in engine frontal area inasmuch as an evaluation of this effect would require detailed design studies that are beyond the scope of this report. The tail-pipe burning and the water injection methods would probably not require changes in engine frontal area, and careful design of bleedoff and rocket-assist installations would involve only slight modification to the airplane.

The weight of additional equipment required for the augmentation methods was estimated from the weight of existing experimental equipment by taking into account any modifications required for aircraft installations.

The following empirical equation was devised to define the additional weight of equipment:

$$\frac{\Delta W}{\Delta F}=\frac{A}{\frac{F_A}{F}-1}+B$$

where

ΔW additional weight, (lb)

ΔF thrust increase, (lb)

A,B constants determined by particular methods under consideration and flight conditions

F_A/F ratio of augmented to normal thrust at the flight conditions under consideration

This equation represents only the weight of additional equipment necessary and does not include any fuel or liquid that must be carried.

The values of A and B were determined for sea-level zero Mach number conditions from the weights of existing equipment; for other conditions of flight Mach number and altitude, A and B were determined by assuming the weight of augmentation equipment as equal to the weight of equipment required for sea-level zero Mach number conditions for operation at the same volume flow of fluids.

The following table lists the values of A and B for the augmentation methods at sea-level zero Mach number conditions and for a flight Mach number of 1.50 at an altitude of 35,332 feet:

Thrust augmentation method	Flight Mach number, 0; altitude, sea level		Flight Mach number, 1.50; altitude, 35,332 ft	
	A	B	A	B
Tail-pipe burning	0.025	0.025	0.045	0.025
Water injection	.020	0	.038	0
Tail-pipe burning plus water injection	.045	.010	.083	.012
Bleedoff	.025	.040	.052	.052

The specific weight of the rocket-assist equipment less propellants was assumed to be constant at a value of 0.075 for all values of thrust augmentation and times of operation. Although the specific weight of rocket engines varies considerably for different units, the value of 0.075 is an average value for several light-weight solid- and liquid-type rocket engines operating for various periods of time up to 4 minutes.

The following table gives the weight of augmentation equipment required for an engine having a normal take-off thrust of 4000 pounds as predicted from the previously mentioned assumption for the given values of augmented thrust ratio; the values listed are for equipment designed for the take-off condition:

Thrust augmentation method	Augmented thrust ratio	Weight of equipment (lb)
Tail-pipe burning	1.5	150
Tail-pipe burning plus water injection	1.8	212
Bleedoff	1.8	227
Rocket	1.8	240

LOAD-RANGE ANALYSIS

The load-range characteristics were determined for a flight Mach number of 1.50 and an altitude of 35,332 feet by the method developed in reference 4. The range of the aircraft for operation with normal turbojet engines and for operation with engines utilizing various amounts of thrust augmentation by each method was determined from the ratio of disposable load (fuel plus tanks plus pay load) to gross weight and the initial liquid rate (pounds liquid per ton-mile). For all conditions, the gross weight of the aircraft was assumed as 150,000 pounds and the lift-drag ratio for the wing was taken as 7. The airplane structure weight was assumed to be 30 percent of the gross weight and the fuel-tank weight to be 10 percent of the fuel weight.

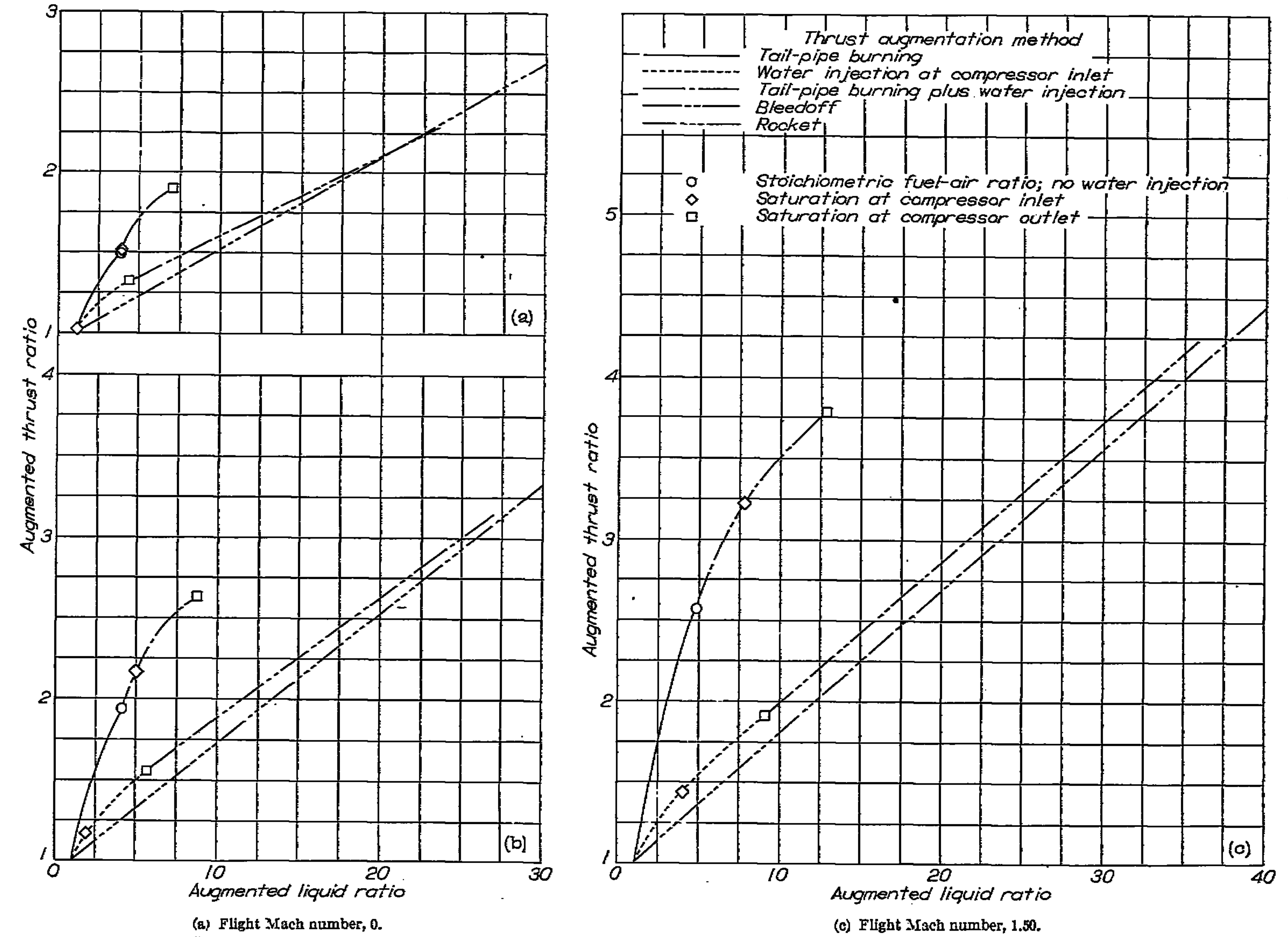
The drag of the entire aircraft was taken as the sum of the drag of the wing plus the nacelle and fuselage drags. The wing drag was found as the product of the gross weight and the wing drag-lift ratio, and the drags of the fuselage and the nacelles were determined using the method and the drag coefficient data presented in reference 4. In order to obtain engine-frontal or nacelle areas, the thrust per unit frontal area of the normal turbojet engine at sea-level zero flight Mach number conditions was assumed to be 800 pounds per square foot. The disposable load was found as the gross weight minus the structure and engine weights. The specific weight of the normal turbojet engine at sea-level zero flight Mach number conditions was assumed to be 0.45 pound engine per pound of thrust, and the weight of augmentation equipment was found in the manner previously described.

RESULTS AND DISCUSSION

THRUST AUGMENTATION

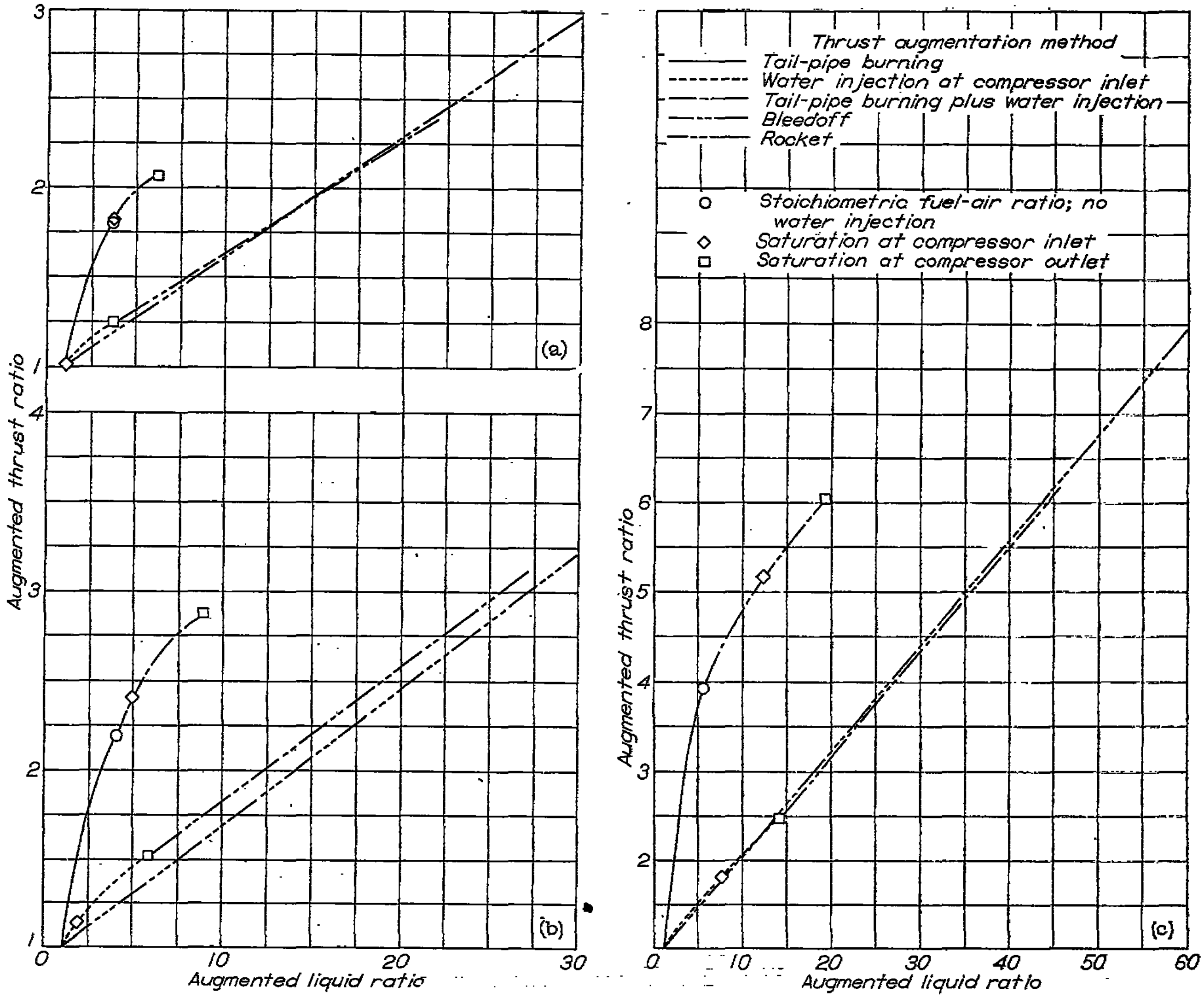
The augmented thrust ratio (ratio of augmented thrust to normal thrust) for the engine having the low-pressure-ratio compressor is shown as a function of augmented liquid ratio (ratio of augmented total liquid consumption to normal total liquid consumption) in figures 2 and 3. In general, the curves for sea-level altitude and flight Mach numbers of 0, 0.85, and 1.50 in figure 2 indicate trends similar to those shown in figure 3 for an altitude of 35,332 feet and for flight Mach numbers of 0.85, 1.50, and 2.50. In the various parts of figures 2 and 3, the occurrence of stoichiometric fuel-air ratio and saturation at the compressor inlet or outlet are indicated by appropriate symbols.

Examination of figures 2 and 3 indicates that for the bleedoff and the rocket-assist methods the augmented thrust ratio increases linearly with increased augmented liquid ratio. For the water injection and the tail-pipe burning methods, the augmented thrust ratio increases rapidly at first and then at a decreasing rate as the augmented liquid ratio is increased. (This effect is more pronounced at low flight Mach numbers.) For the present analysis, the combination tail-pipe burning plus water injection method has been considered only for an over-all stoichiometric fuel-air ratio and the curves for the combination tail-pipe burning plus water injection method therefore appear as extensions of the curves for tail-pipe burning alone and have the same general shape as the curves for water injection alone. For the bleedoff method, it has been assumed that sufficient water has been injected at the compressor inlet to saturate the compressor-outlet air; the curves for bleedoff therefore appear as extensions to the curves for water injection alone.



(a) Flight Mach number, 0.
(b) Flight Mach number, 0.85.
(c) Flight Mach number, 1.50.

FIGURE 2.—Augmented thrust ratio as function of augmented liquid ratio for sea-level altitude.



(a) Flight Mach number, 0.85.
(b) Flight Mach number, 1.50.
(c) Flight Mach number, 2.50.

FIGURE 3.—Augmented thrust ratio as function of augmented liquid ratio for altitude of 35,332 feet.

The relative performance of the various augmentation methods remains substantially unchanged with changes in flight Mach number and altitude, as shown in figures 2 and 3. The water injection method is limited to the lowest maximum values of thrust augmentation of any of the methods considered, whereas the tail-pipe burning method provides a considerably increased amount. Still larger values of augmented thrust ratio are possible for the combination tail-pipe burning plus water injection and the bleedoff methods, and there is, theoretically, no limit to the augmented thrust ratio available for rocket assist.

Considered on the basis of lowest augmented liquid ratio for all altitudes and flight Mach numbers, the combination tail-pipe burning plus water injection method appears best for large increases in thrust and the tail-pipe burning method is best for smaller amounts of augmentation. Although the water injection method is limited to smaller values of augmented thrust ratio than the tail-pipe burning method, the water injection method does have the advantage of simplicity of installation and operation. The bleedoff and rocket-assist methods provide greater amounts of augmentation than are possible from the combination tail-pipe burning plus water injection method but at the expense of very high liquid consumptions. For a given augmented thrust ratio, the required augmented liquid ratios for the bleedoff and the rocket-assist methods are approximately equal at all flight conditions.

For sea-level zero flight Mach number conditions (fig. 2(a)), the maximum augmented thrust ratio obtainable for the tail-pipe burning method is approximately 1.5 with a required total liquid consumption of four times that for the normal engine. The maximum augmented thrust ratios obtainable for water injection, combination tail-pipe burning plus water injection, and bleedoff methods are 1.3, 1.9, and 2.3, respectively. The augmented liquid ratios associated with these values of augmented thrust ratio are 4.4, 7.0, and 23.3, respectively. As was stated previously, for a given thrust increase the augmented liquid ratio for rocket assist is about equal to that for bleedoff and is approximately two times that required for the combination tail-pipe burning plus water injection method.

The effect of flight Mach number can be determined by comparing figures 2(a), 2(b), and 2(c). In general, the effect of increasing flight Mach number is to increase the augmented thrust ratio for a given augmented liquid ratio and to increase the maximum augmented liquid ratio possible.

For the tail-pipe burning method of augmentation at an augmented liquid ratio of 4, increasing the sea-level flight Mach number from 0 to 1.50 increases the augmented thrust ratio from 1.5 to 2.3. The maximum augmented liquid ratio increases from 4 to 5 for the same increase in flight Mach number, providing a maximum augmented thrust ratio of nearly 2.6 at a flight Mach number of 1.50. Similar increases in performance of the other methods also accompany increases in flight Mach number. The effect of flight Mach number at an altitude of 35,332 feet (fig. 3) is similar to the effect at sea level (fig. 2).

In general, for a constant augmented liquid ratio, increasing the altitude somewhat decreases the augmented thrust ratio, as indicated by comparison of figures 2 and 3. This effect is very slight for the tail-pipe burning method, but is appreciable for those methods employing water injection at the compressor inlet because of the decreased amount of water that may be evaporated at the decreased temperatures accompanying increased altitudes. For example, for the water injection method operating at a flight Mach number of 1.50 and an augmented liquid ratio of 6, the augmented thrust ratio decreases from 1.62 to 1.51 as the altitude is increased from sea level to 35,332 feet; for the tail-pipe burning method at a flight Mach number of 1.50 and an augmented liquid ratio of 4, the decrease is from 2.3 to 2.2

The effect of altitude on maximum augmented thrust ratio and maximum augmented liquid ratio for a flight Mach number of 0.85 is shown in figure 4. The effect of altitude on maximum augmented thrust ratio is somewhat greater but similar to the effect previously described for a

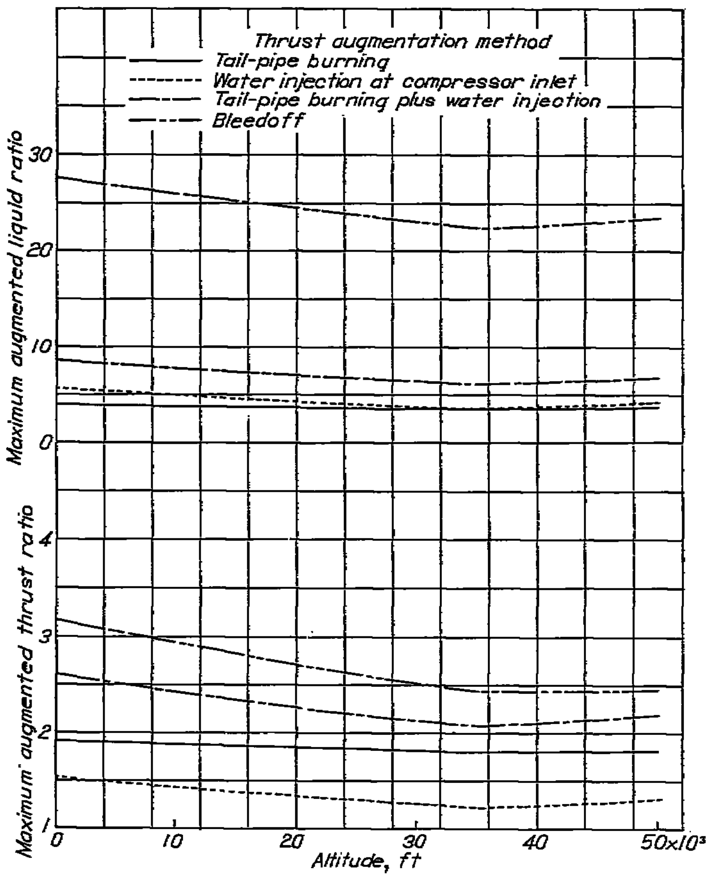


FIGURE 4.—Maximum augmented thrust and maximum augmented liquid ratios as functions of altitude for flight Mach number of 0.85.

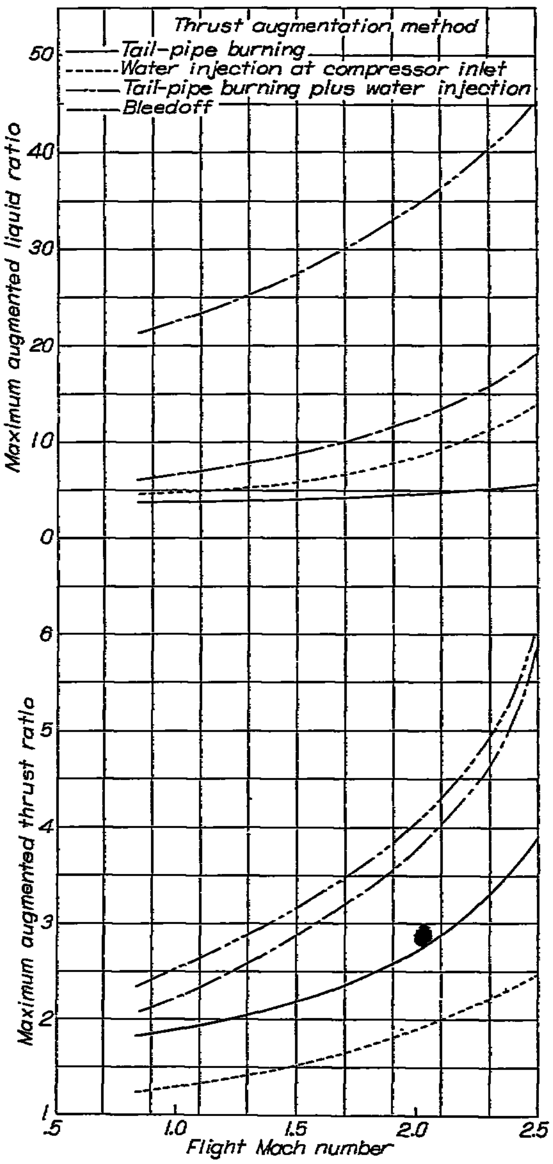


FIGURE 5.—Maximum augmented thrust and maximum augmented liquid ratios as functions of flight Mach number for altitude of 35,332 feet.

constant augmented liquid ratio. The maximum augmented thrust ratio remains approximately constant as the altitude is increased for the tail-pipe burning method, and slightly decreases for altitudes up to 35,332 feet for those methods employing water injection at the compressor inlet. The slight increase in augmented thrust ratios as altitude is increased above 35,332 feet for those methods employing water injection is due to the decreased ambient pressure (constant ambient temperature), which permits the evaporation of more water. The augmented liquid ratios follow the same general trends as the augmented thrust ratios.

The effect of flight Mach number on maximum augmented thrust ratio and maximum augmented liquid ratio for an altitude of 35,332 feet is shown in figure 5. All methods show a marked increase in augmented thrust ratio as the flight Mach number is increased; for example, an increase in flight Mach number from 0.85 to 2.50 results in a two- to three-fold increase in augmented thrust ratio for all methods. The augmented liquid ratio increases with flight Mach number in a manner similar to the increase in augmented thrust ratio

All the previously discussed results are for an engine having a low-pressure-ratio compressor. In order to illustrate the effect of increased compressor pressure ratio, the performance of engines having high- and low-pressure-ratio compressors is compared for operation at sea-level altitude and a flight Mach number of 0.85 in figure 6. In the common range of

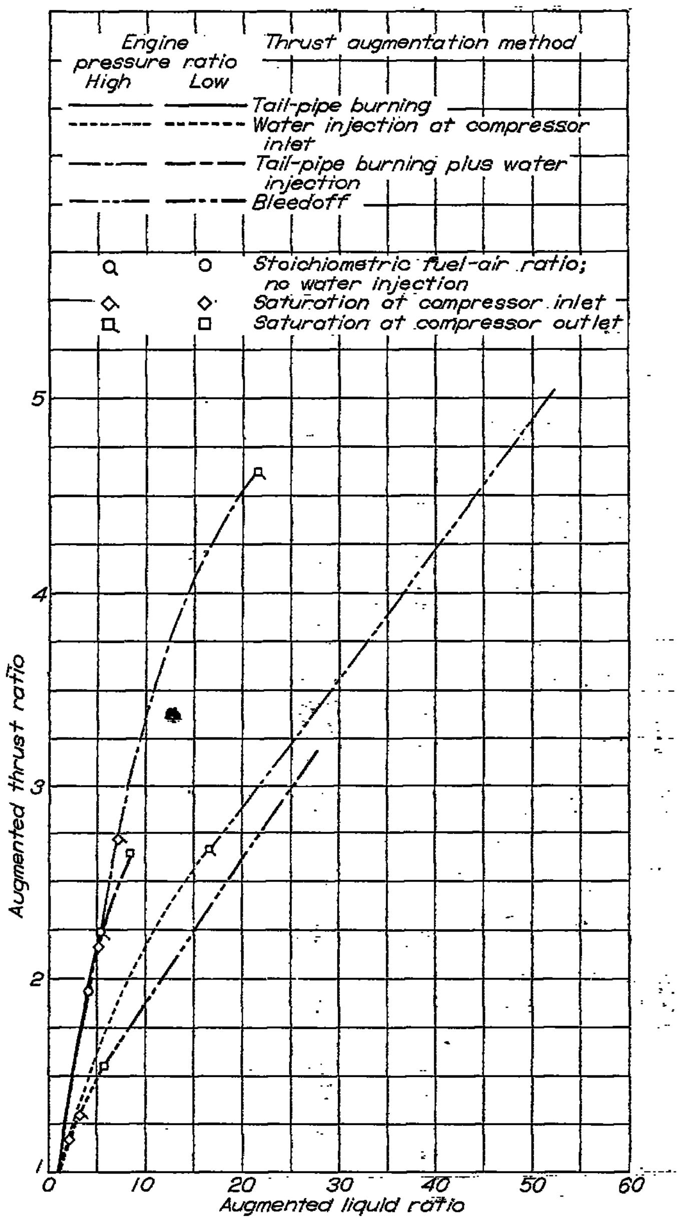


FIGURE 6.—Comparison of performance of various thrust augmentation methods for low- and high-pressure-ratio engines. Altitude, sea level; flight Mach number, 0.85.

augmented liquid ratios, there is very little difference between the augmented thrust ratios obtained from the low- and high-pressure-ratio engines at a constant augmented liquid ratio. High compressor pressure ratios do, however, increase the maximum augmented thrust ratio for all methods by permitting increased maximum augmented liquid ratios with the greatest gains being obtained for those methods utilizing water injection. For the tail-pipe burning method, the maximum augmented thrust ratio for the low-pressure-ratio engine is 1.9 as compared to 2.2 for the high-pressure-ratio engine; for the combination tail-pipe burning plus water injection method, the maximum augmented thrust ratio increases from 2.6 to 4.6.

TAKE-OFF CONSIDERATIONS

A comparison of take-off weights of augmented and normal turbojet engines is shown in figure 7. The ratio of the weight of engine plus augmentation equipment plus fuel and liquid to the weight of the normal engine plus fuel is shown as a function of augmented thrust ratio for each of the augmentation methods. The weight of fuel and liquids used in this comparison was sufficient for 6 seconds of operation to provide for the initial climb of the aircraft at the end of the ground run. Any additional fuel and liquid weight required for the augmented engine during the ground run has been neglected inasmuch as this weight could be carried as overload. In all cases, the additional weight due to fuel and liquids is less than one-third of the total additional weight and therefore initial climb periods somewhat less or greater than 6 seconds would not appreciably affect the comparison. The weight of additional equipment was obtained in the manner previously described.

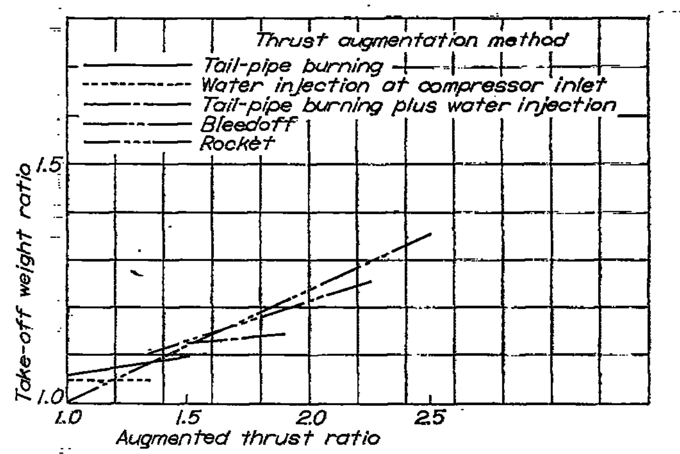


FIGURE 7.—Variation at take-off of the ratio of weight of engine plus augmentation equipment plus fuel and liquid to the weight of normal engine plus fuel with augmented thrust ratio.

The best augmentation method for take-off conditions from additional weight considerations depends on the amount of augmentation required, and each method has a particular range of augmented thrust ratios where it is the most desirable. For values of augmented thrust ratio less than 1.2, the rocket-assist method involves the least additional weight; for values of augmented thrust ratio from 1.5 to 1.9, the combination tail-pipe burning plus water injection method is best; and for greater values of augmented thrust ratio, the bleedoff method, up to its maximum, involves the least additional weight. For a required take-off augmented thrust ratio of 1.8, the engine equipped for augmentation by tail-pipe burning plus water injection is 14 percent heavier than the normal engine; the specific weight, however, is less because of the increased thrust.

LOAD-RANGE CHARACTERISTICS

The results of the load-range analysis, which was made for an altitude of 35,332 feet and a flight Mach number of 1.50, are presented in figures 8 and 9. In figure 8, the ratio of disposable load to airplane gross weight is plotted against liquid rate per mile per ton of gross weight for each of the augmentation methods. The slope of a line drawn from the origin through any point on a curve represents the range for the condition where all the disposable load is fuel. The range for any desired amount of pay load can be found from the slope of a line drawn from the origin through a point corresponding to the initial fuel rate and the ratio of fuel load (disposable load minus pay load) to aircraft gross weight. A scale of range in miles has been included in figure 8 for reference. Each curve represents the performance of a particular augmentation scheme with the amount of augmentation increasing in a direction from left to right along the curves. The performance for operation with the normal turbojet engine is indicated by a triangle, and for this condition the aircraft has a range of 800 miles. The initial point for tail-pipe burning occurs at a thrust ratio somewhat less than 1 and at a lower disposable load and maximum range than the normal engine because of the loss in thrust due to pressure losses in the nonoperating tail-pipe burner. As the augmented thrust ratio for the tail-pipe burning method is increased (moving upward along the curve), the ratio of disposable load to gross weight and the range are increased; further increase in augmented thrust ratio results in an increased ratio of disposable load to gross weight but a decreased maximum range. The maximum range for the engine utilizing tail-pipe burning is 925 miles or an increase of 15 percent over that for the normal engine. The augmented thrust ratio for this point of maximum range is approximately 1.6.

For an altitude of 35,332 feet and a flight Mach number of 1.50, the tail-pipe burning method of augmentation is the only method, which, when used for the entire flight time, will increase the range over that obtained with a normal engine (fig. 8). Although none of the other methods allows an increase in maximum range, they do permit large increases in ratio of disposable load to gross weight.

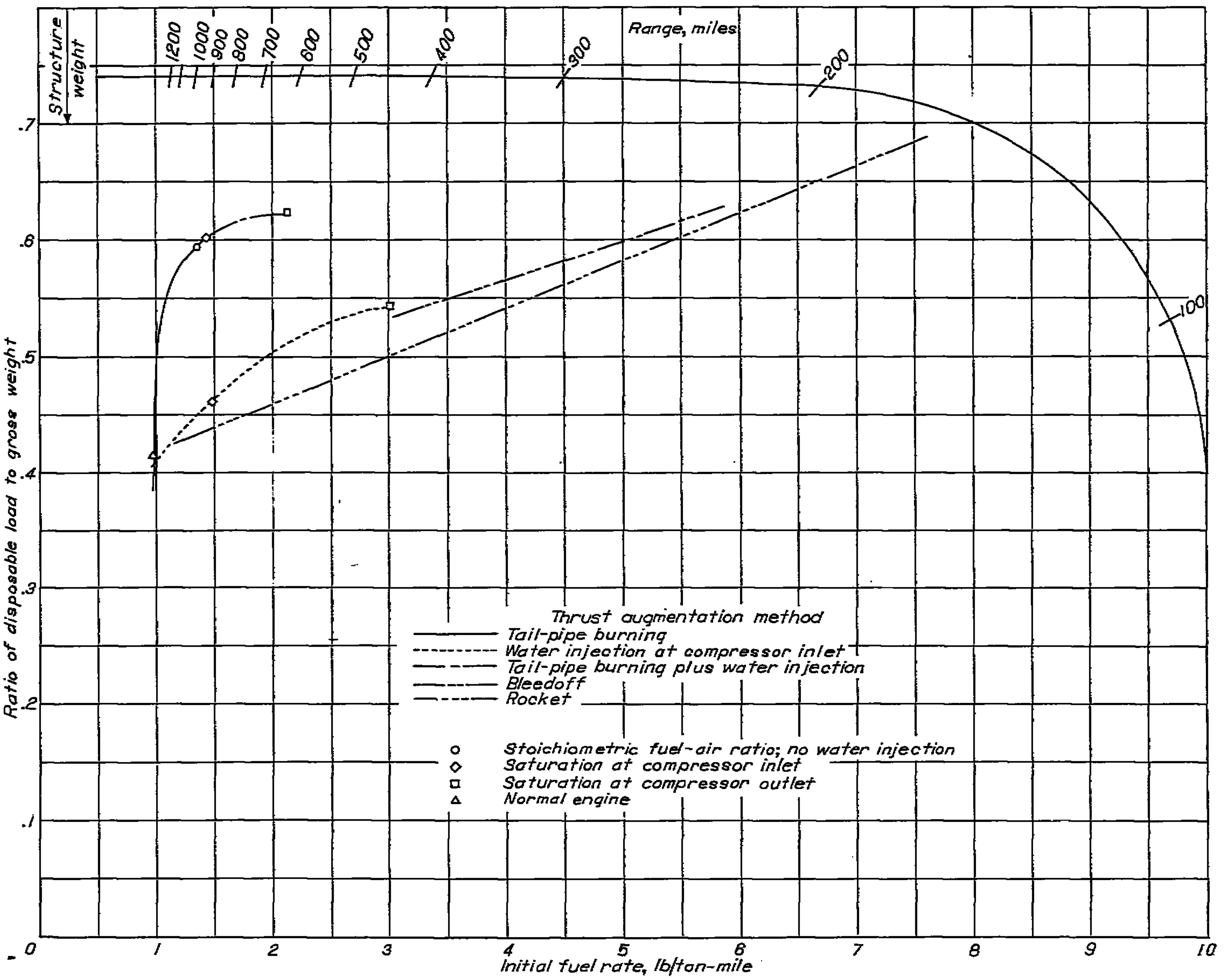


FIGURE 8.—Load-range characteristics of airplane powered by augmented turbojet engines. Altitude, 35,332 feet; flight Mach number, 1.50.

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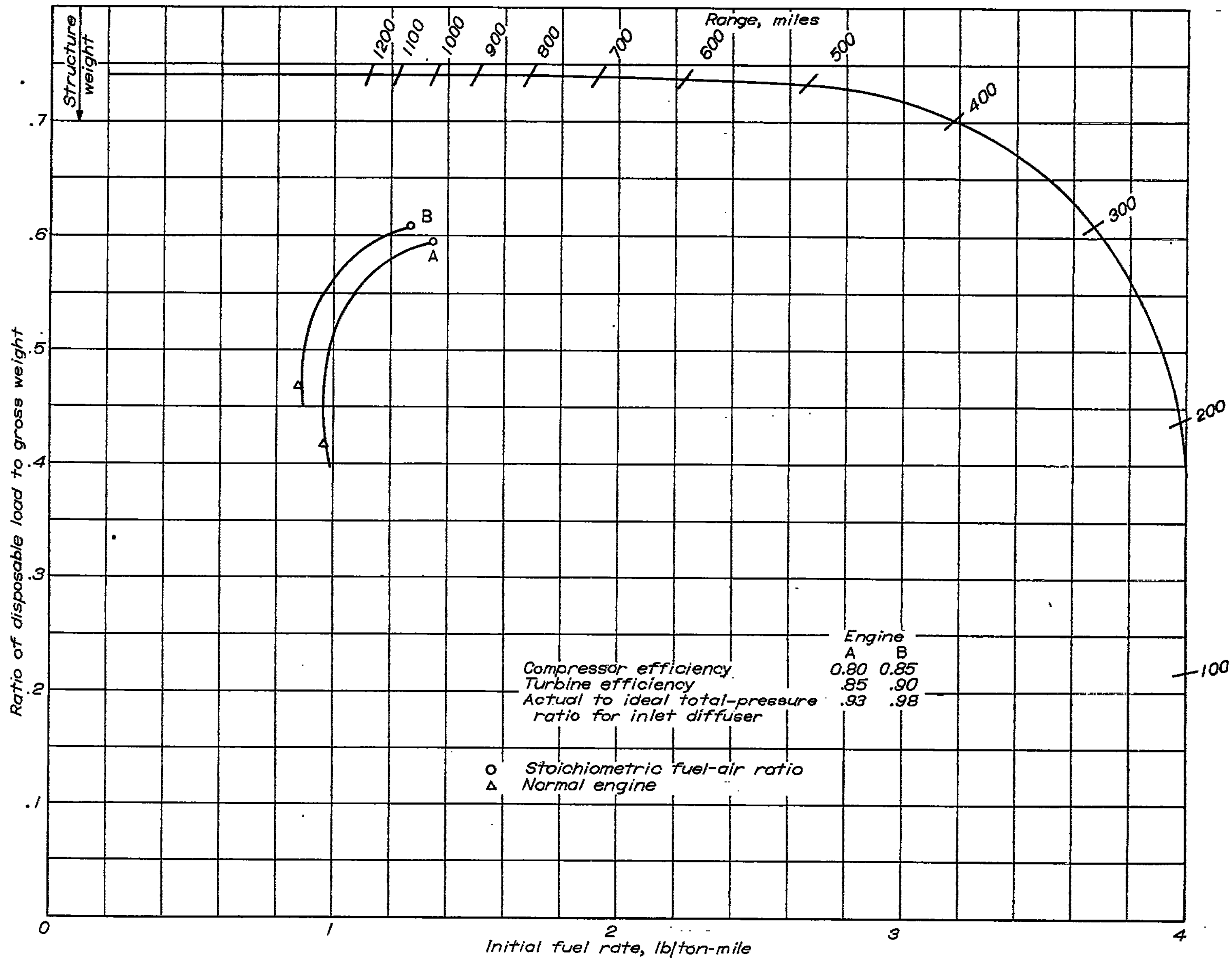

FIGURE 9.—Effect of increased component efficiencies on load-range characteristics of airplane powered by turbojet engines utilizing tail-pipe burning. Altitude, 35,332 feet; flight Mach number, 1.50.

The preceding results are based on the rather conservative estimates of engine component performance previously described. In order to determine whether these results would also apply to an engine having more efficient components, the calculations were repeated for the tail-pipe burning method with the following revisions: the compressor and turbine efficiencies were increased from 0.80 to 0.85 and from 0.85 to 0.90, respectively, and the ratio of actual to ideal total pressure for the inlet diffuser was increased from 0.93 to 0.98. The results of these calculations are presented in figure 9. The results for the engine having improved component efficiencies and utilizing the tail-pipe burning method of augmentation is labeled engine B in figure 9. For comparison, the results for the tail-pipe burning method obtained from figure 8 are included and labeled engine A. In view of the increased performance of engine B, the thrust produced per unit frontal area has been increased from 800 to 875 pounds per square foot, whereas the specific weight of the engine has been decreased from 0.45 to 0.41 pound engine per pound of thrust. For engine B, the gross weight of the aircraft was maintained equal to that for engine A.

For engine B, the maximum range of the aircraft was increased from 970 miles for the normal configuration to 1045 miles for the configuration utilizing tail-pipe burning, an increase of about 8 percent as compared to a 15-percent increase for engine A. The augmented thrust ratio for maximum range is 1.6 for both engines. Although the increase in range obtained by the addition of tail-pipe burning for engine B is less than for engine A, the augmentation of a highly efficient engine with tail-pipe burning will slightly increase the maximum range and provide a considerable increase in disposable load per unit gross weight at ranges less than the maximum.

SUMMARY OF RESULTS

A theoretical comparison of various methods of thrust augmentation for turbojet engines indicated the following results:

1. For all conditions of flight Mach number and altitude, the combination tail-pipe burning plus water injection method was best for obtaining large amounts of thrust augmentation, whereas the tail-pipe burning method was best for smaller amounts inasmuch as these methods had the lowest augmented liquid ratio for a given augmented thrust ratio of any of the methods considered. Although the water injection method was limited to lower values of augmented thrust ratios and higher augmented liquid ratios than the tail-pipe burning method, the water injection method has the advantage of simplicity of installation and operation. For sea-level zero Mach number conditions, the maximum augmented thrust ratio for the combination tail-pipe burning plus water injection method was 1.9 at an augmented liquid ratio of 7; for the tail-pipe burning method the maximum augmented thrust ratio was 1.5 at an augmented liquid ratio of 4.

2. Increasing the flight Mach number greatly increased both the maximum augmented thrust ratio and the augmented thrust ratio for a given augmented liquid ratio for all the methods considered. Increasing the altitude of operation decreased somewhat the augmented thrust ratio for all the methods utilizing water injection. The effect of increased altitude on the augmented thrust ratio produced by the tail-pipe burning method was very slight.

3. The principal effect of high compressor pressure ratio was to increase the maximum possible augmented liquid ratio and hence the maximum augmented thrust ratio. Over the common range of augmented liquid ratios, the effect of increased compressor pressure ratio was slight.

4. The most desirable method of thrust augmentation on the basis of least additional take-off weight was found to be dependent on the required amount of augmentation with each method considered being best for a certain range of augmented thrust ratios near the maximum for the particular method. For small amounts of augmentation the rocket-assist method was best and for very large amounts of augmentation the bleedoff method involved the least additional take-off weight.

5. For a flight Mach number of 1.50 and an altitude of 35,332 feet, the tail-pipe burning method allowed a slightly increased maximum range of a representative aircraft and a considerable increase in disposable load. The other augmentation methods considered permitted large increases in disposable load at the expense of reduced range.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, *October 27, 1948.*

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